Developing the Next Generation NATO Reference Mobility Model

Dr. Michael McCullough, BAE Systems Platforms and Services
Dr. Paramsothy Jayakumar, U.S. Army TARDEC
Dr. Jean Dasch, Alion Science and Technology
Dr. David Gorsich, U.S. Army TARDEC

AGENDA

- Introduction
- NRMM Overview
- Requirements
- Methodologies
- Stochastics
- Intelligent Vehicles
- Tool Choices
- Input/Output Data
- Verification and Validation
- Conclusions

NATO Reference Mobility Model (NRMM)

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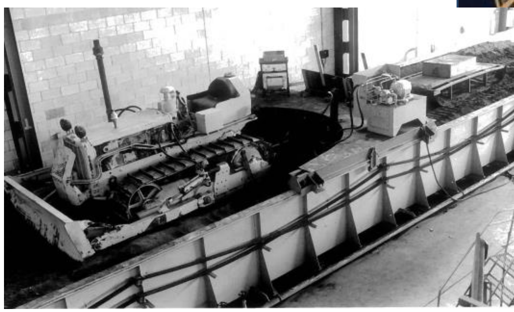
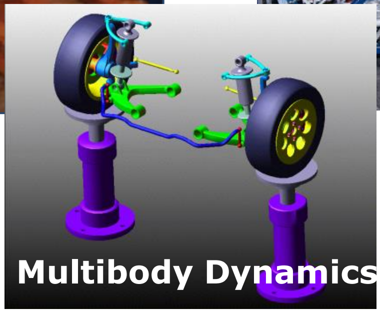
Walking Machine



Land Locomotion



Autonomous Systems

1954 – Land Locomotion Lab established; led by Dr. Bekker

1971: AMC-71 Mobility Model

1974: AMC-74 Mobility Model

1978: NATO Reference Mobility Model

1992: NRMM II

2004: Packbot in NRMM

2014: ET148, NG-NRMM

2016: RTG248 NG-NRMM

2019: NG-NRMM STANAG

1950 1960 1970 1980 1990 2000 2010 2020

NRMM has a valuable legacy, but requires an open architecture to support current and future terrain vehicle system modeling requirements

NRMM Overview

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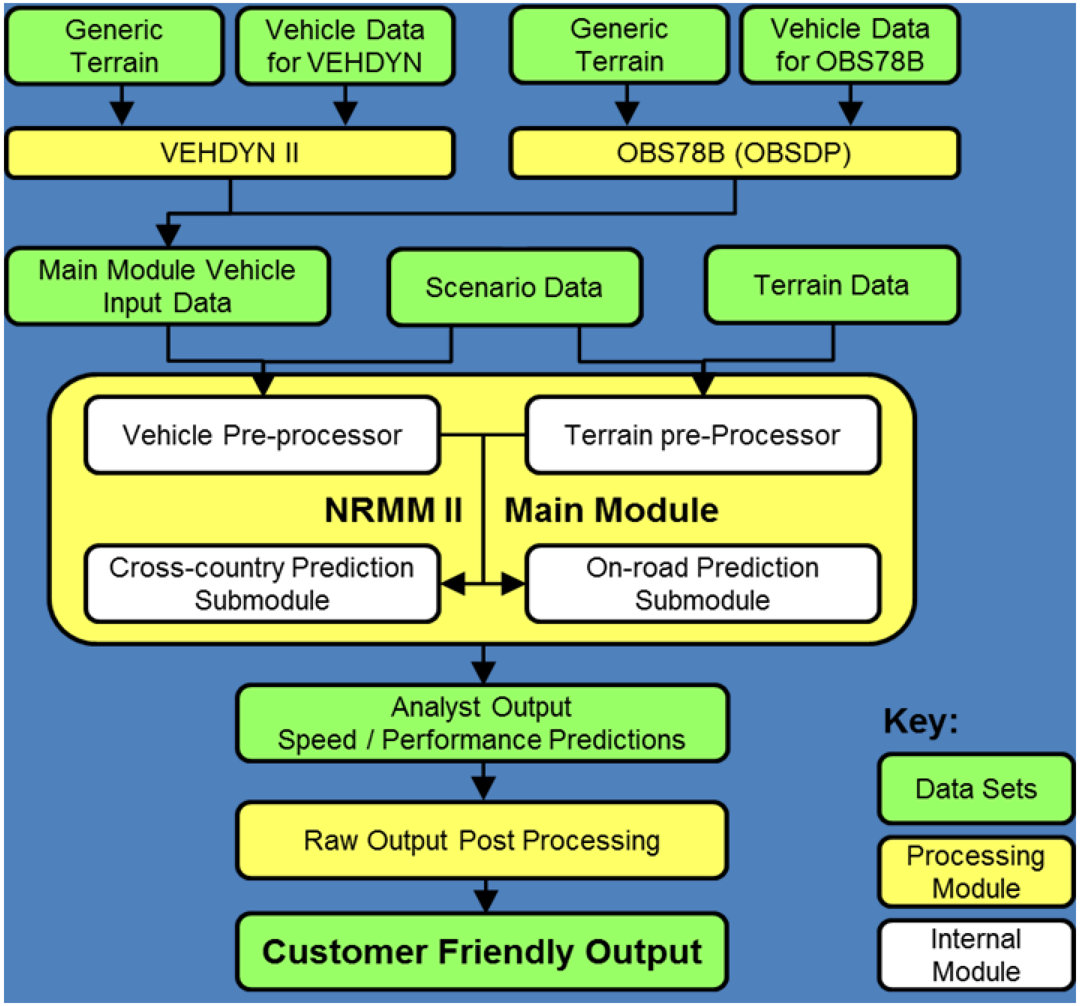
- FORTRAN code
- 2D pitch plane vehicle dynamic models for ride quality and obstacle performance
- Terrain data are maps of soil, slopes, vegetation, roads, obstacles for specific world regions
- Scenario data overlays weather effects
- Main operational module considers seven major speed limiting factors
- Empirical soft soil trafficability models based on rating and vehicle cone index (RCI / VCI)
- Widely used for
  - operational analysis
  - acquisition
  - design



Vehicle Dynamics Model Substitution

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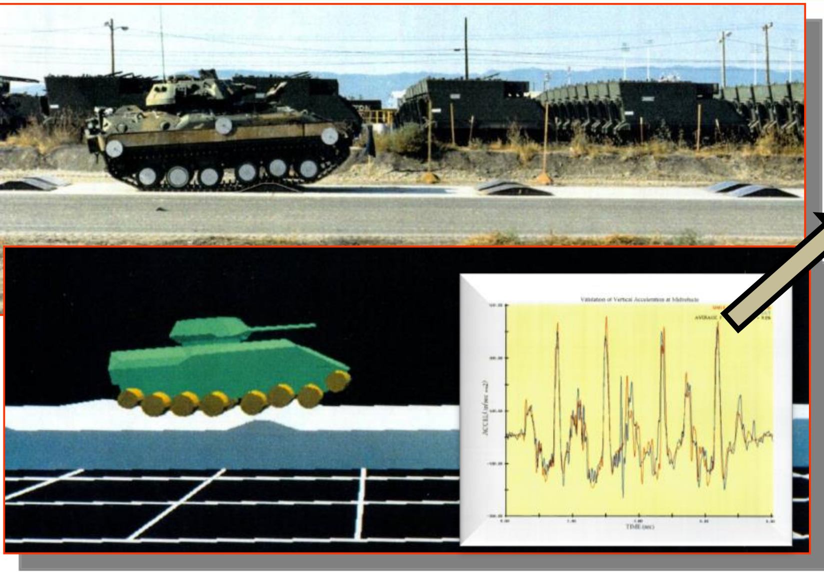
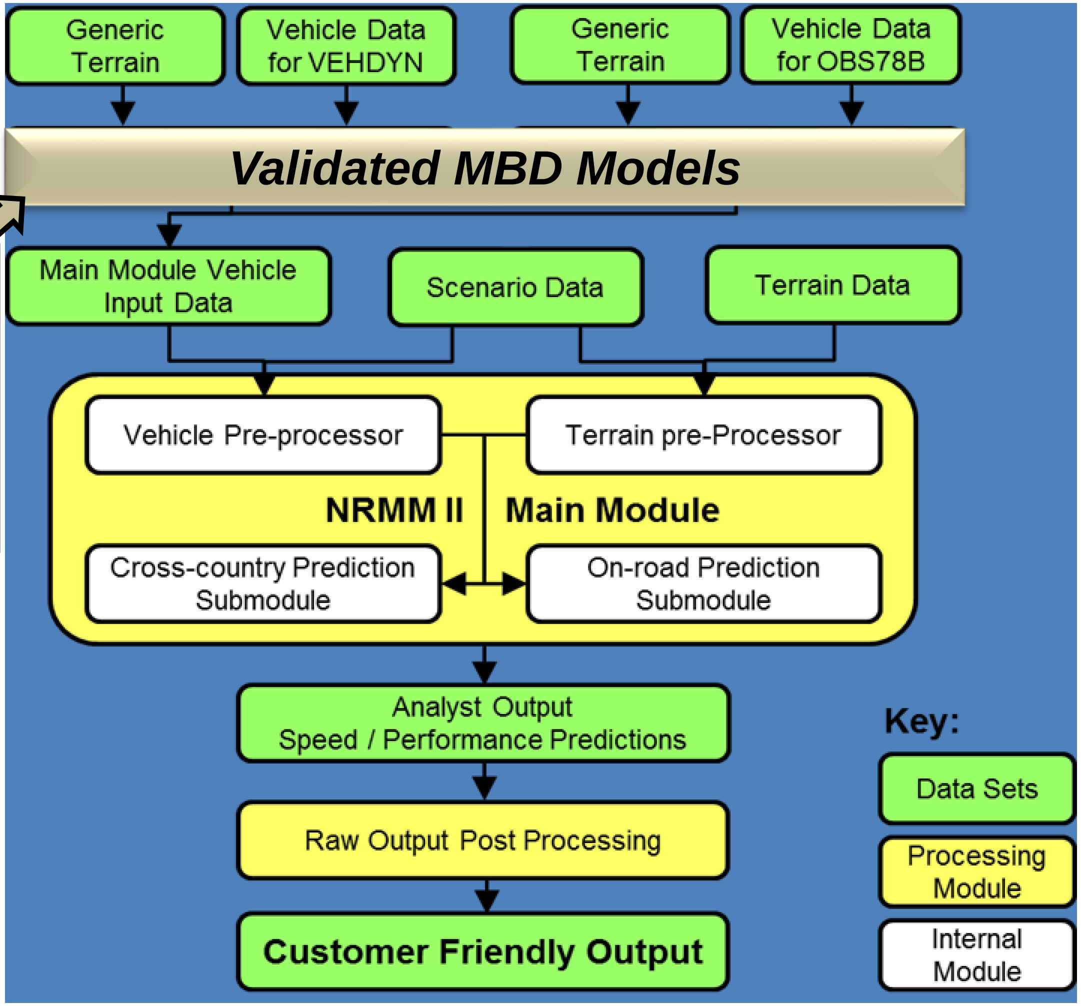
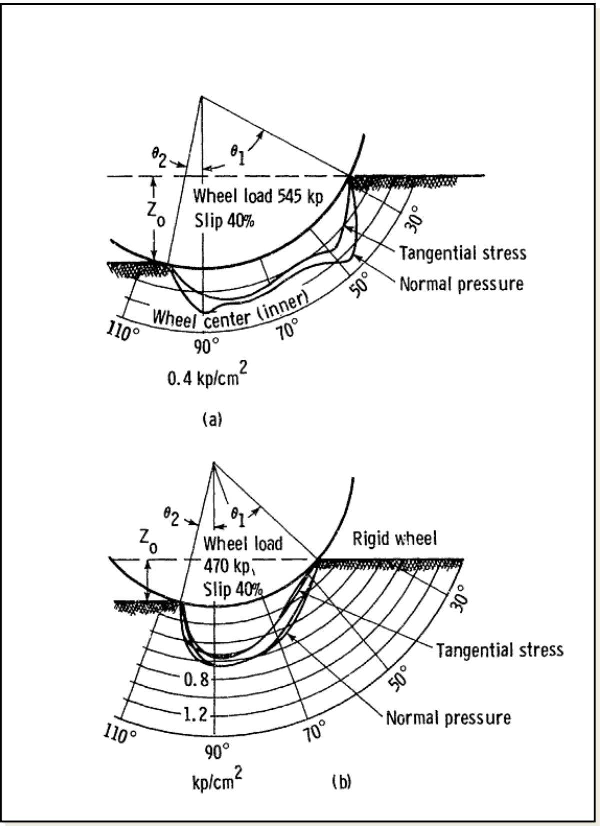




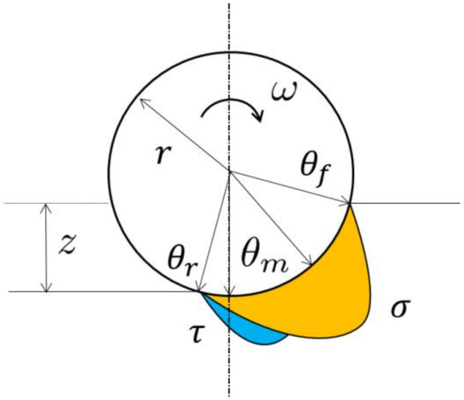
The advent of validated 3D multi-body dynamics modeling tools has resolved some vehicle dynamic model limitations, but mobility metrics should be expanded to match the modeling capabilities

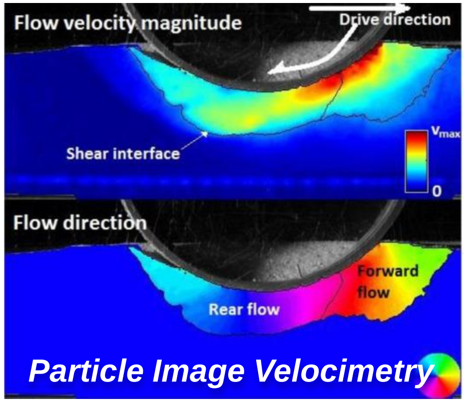
Next Generation Terramechanics

FEM Plastic Limit Theory

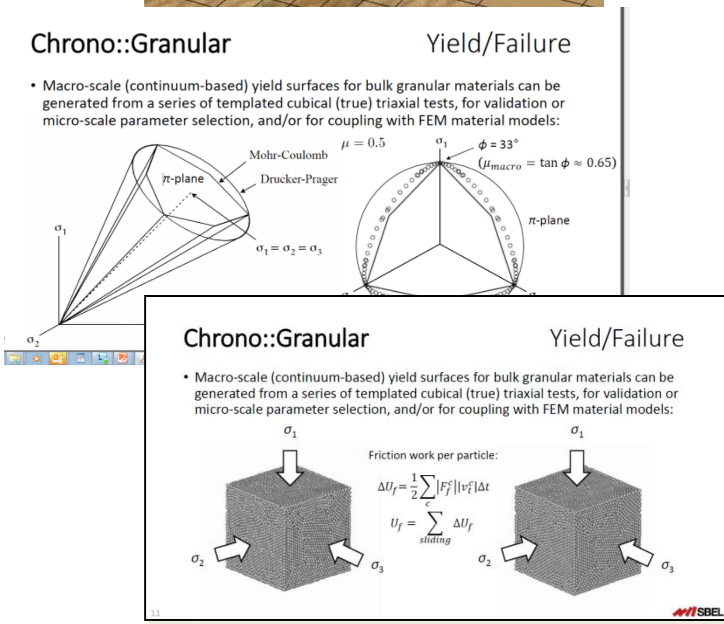


Bekker-Wong-Janosi models





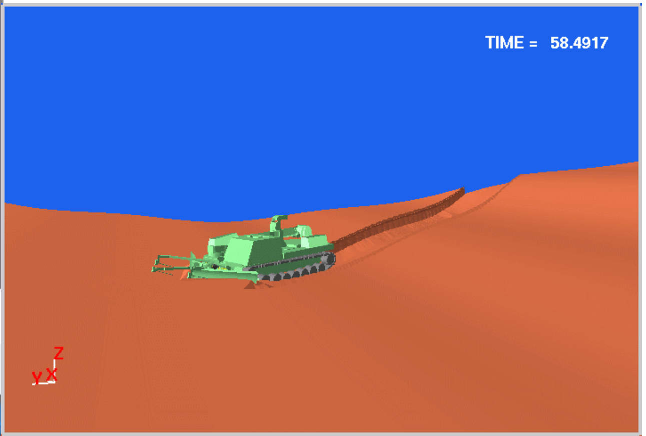
Discrete element models (DEM)

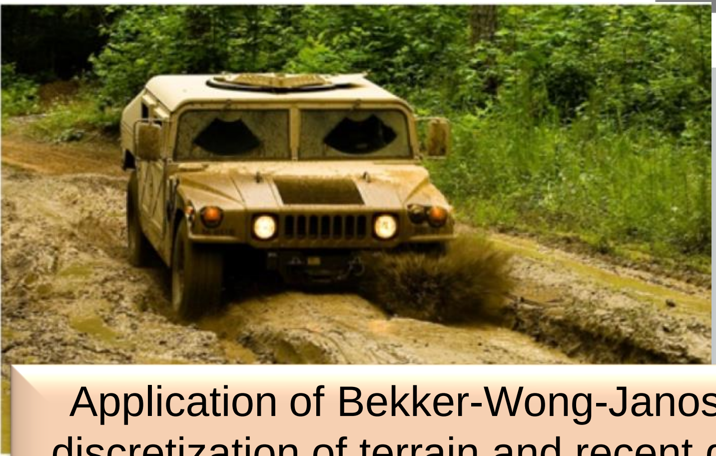


From cone index to a new soil strength index, SSI(ρ,c,ϕ,D,e,MC)

Vehicle Performance Modeling in Soft Soil

Field test calibrated height field and soil cutting/flow models in DADS ~1999

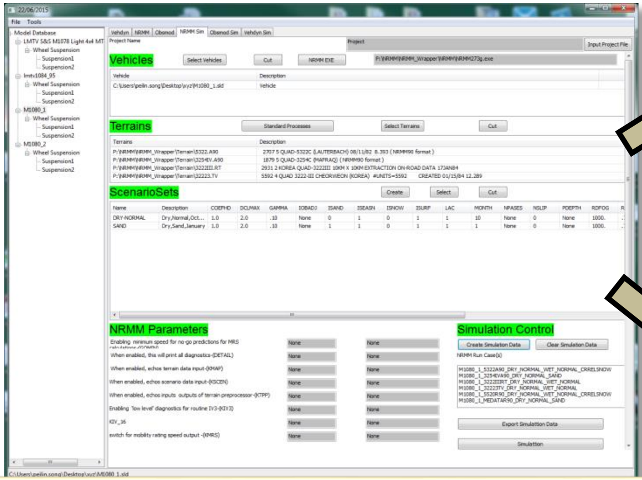




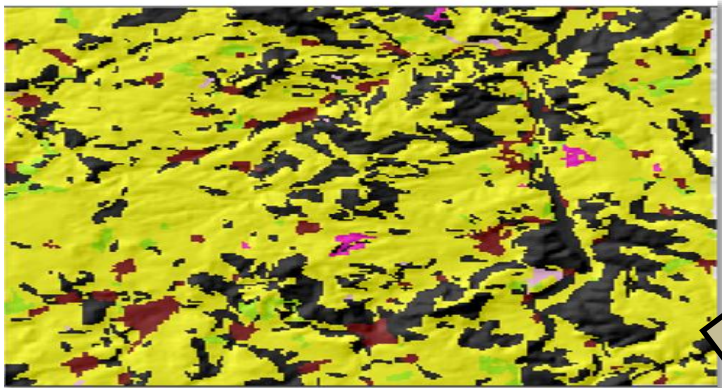
Discrete element models (DEM) on high performance computers (HPC) ~2014

Application of Bekker-Wong-Janosi models through height field discretization of terrain and recent developments in DEM are two leading candidates for higher fidelity soft soil modeling.

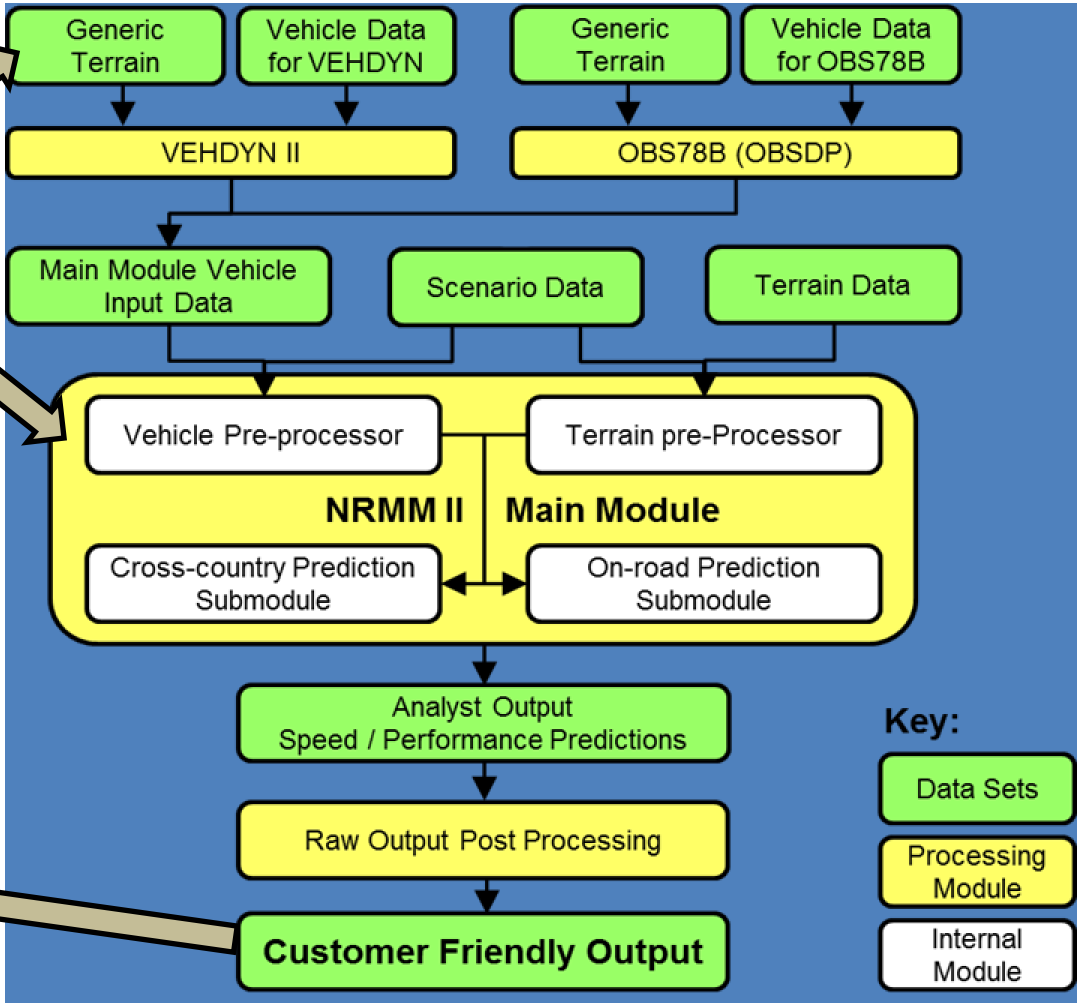
Next Gen Pre and Post Processors



AMSAA SLAMD Graphical User Interface



AMSAA Mobility Maps in COTS GIS s/w



GIS data and modeling tools have significantly expanded terrain modeling goals for NG-NRMM

Urban Environments

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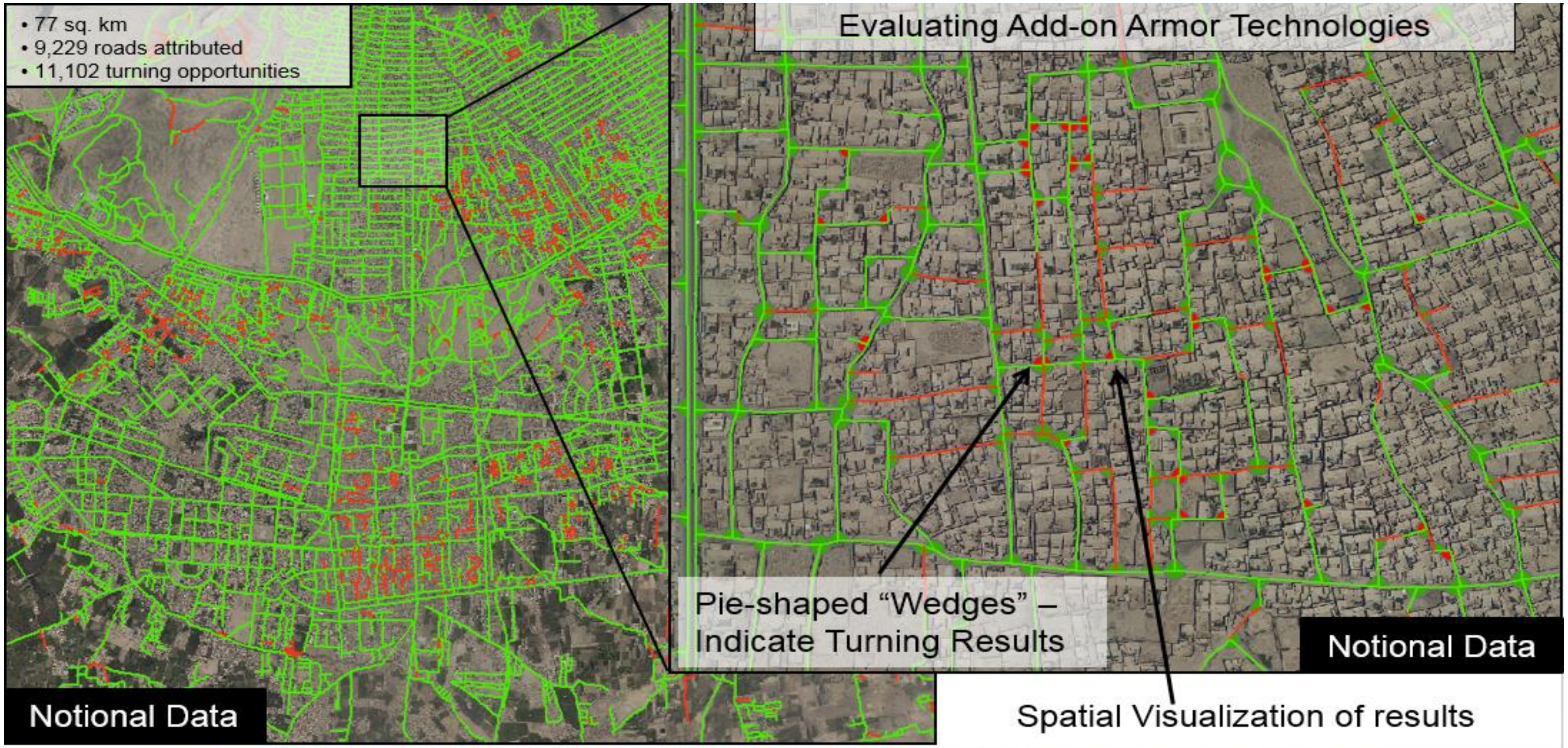

- Graphic depicts Go / NoGo roads and turning combinations for the example vehicle with add-on armor applied
- AMSAA modeling methodology evaluates the vehicle's physical dimensions and turning capability on its performance in operational environments
- Product delivered to operational commander to inform mission planning

AMSAA Urban Maneuverability Model (UMM) is already extending mobility analysis to urban environments

NG-NRMM Requirements

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Category	Sub-category	Near-Term Priorities for NG-NRMM	Far-Term Priorities for NG-NRMM
New System Capabilities	Vehicle Type	Wheeled, tracked, autonomous	Legged, autonomous
	Vehicle Scale	Conventional manned vehicles	Lighter and smaller vehicles
	Terrain Scale	Regional, varied resolutions	Global, varied resolutions
New Modeling Capabilities	Suspension Types	Passive, semi-active, active	Active
	Control Types	Driver, ABS, TCS, ESC, ABM, CTIS, autonomy	Autonomy
	Sub-systems	Steering, powertrain, autonomy	Autonomy, human cognition
	Model Features	3D Physics based running gear scale deformable terrain models (e.g. Bekker/Wong, others) Multibody/flexible body vehicle models Detailed tire and track models	Deformable, dynamic terrain (e.g., FEM, discrete elements) Stochastic models
New Analysis Capabilities	User Type	Analyst/Expert	Operational Planner
	Environment Types	On-road, off-road, urban rubble, soil, snow/ice	Urban (all)
	Powertrain Performance	Grading, turning, fuel economy	Cooling
	Amphibious Operations	Fording, swimming	
	Computations	Computational Efficiency - fidelity trade off	High fidelity and high performance
New Output Capabilities	Assessment Types	Performance in operational context	
	Metric Considerations	M&S Accreditable mobility metrics	

A thorough process of requirements development resulted in a focused set of development goals partitioned in two phases

NG-NRMM Methodologies

- "Open architecture" refers to an enduring realization of NG-NRMM that is implemented at a higher level of abstraction that:
  - includes all current validated legacy models and input data,
  - non-preferentially allows a variety of implementation environments
  - promotes future innovation across all required gap areas.
- Implemented thru NATO Operational Reference Mobility Modeling Standards (NORMMS):
  - applicable to the full range of ground vehicle geometric scales
  - promoting modeling software standardization, integration, modular interoperability, portability, and expansion,
  - include verification and validation benchmarks of vehicle-terrain interaction models at multiple levels of theoretical and numerical resolution
  - for use in vehicle design, acquisition and operational mobility planning

An open architecture was established as foundational goal, using formal mobility modeling standards as the primary mechanism for implementation

Methodology: Use standards to leverage COTS simulation tools

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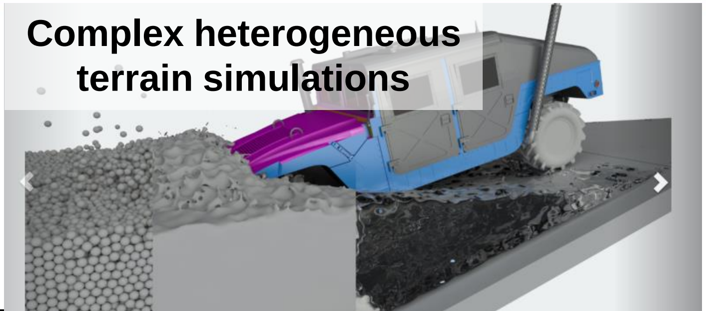
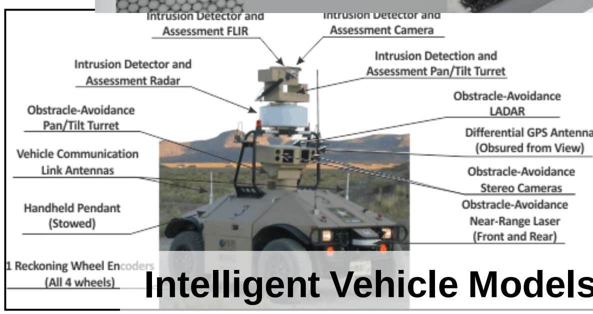
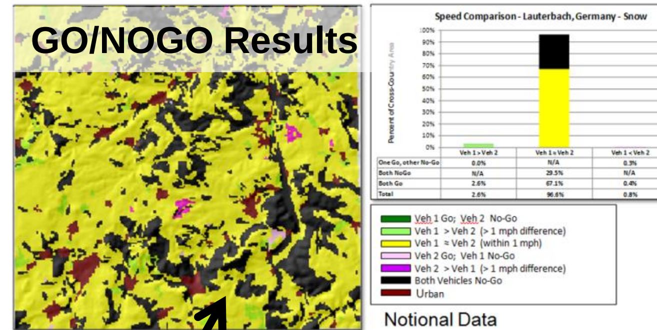
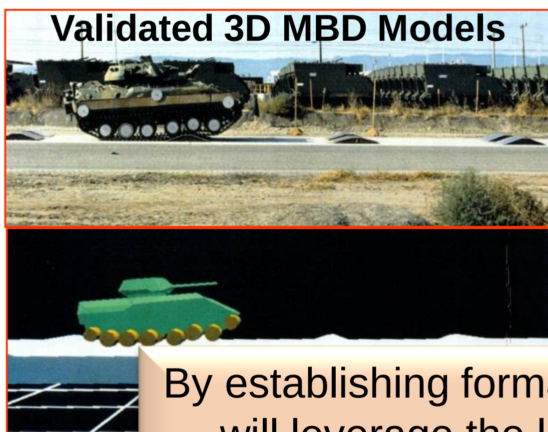


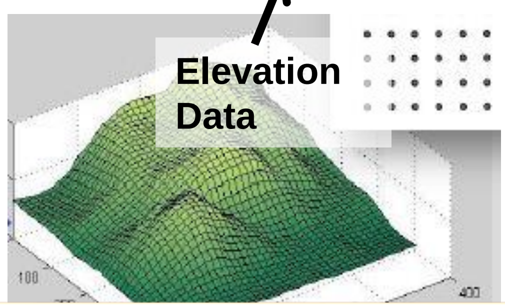


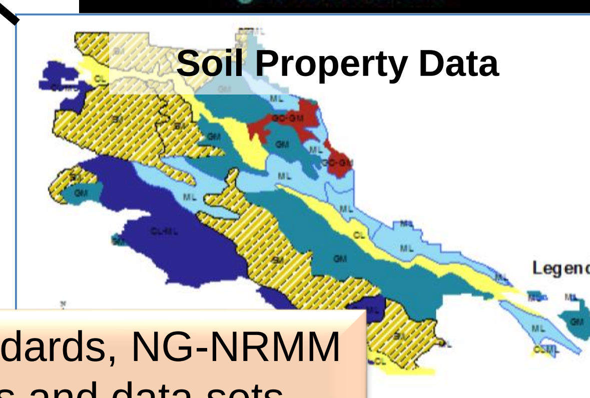
Visualization and analysis of multiple vehicle outputs using ArcGIS (COTS) software.



Next Generation NRMM







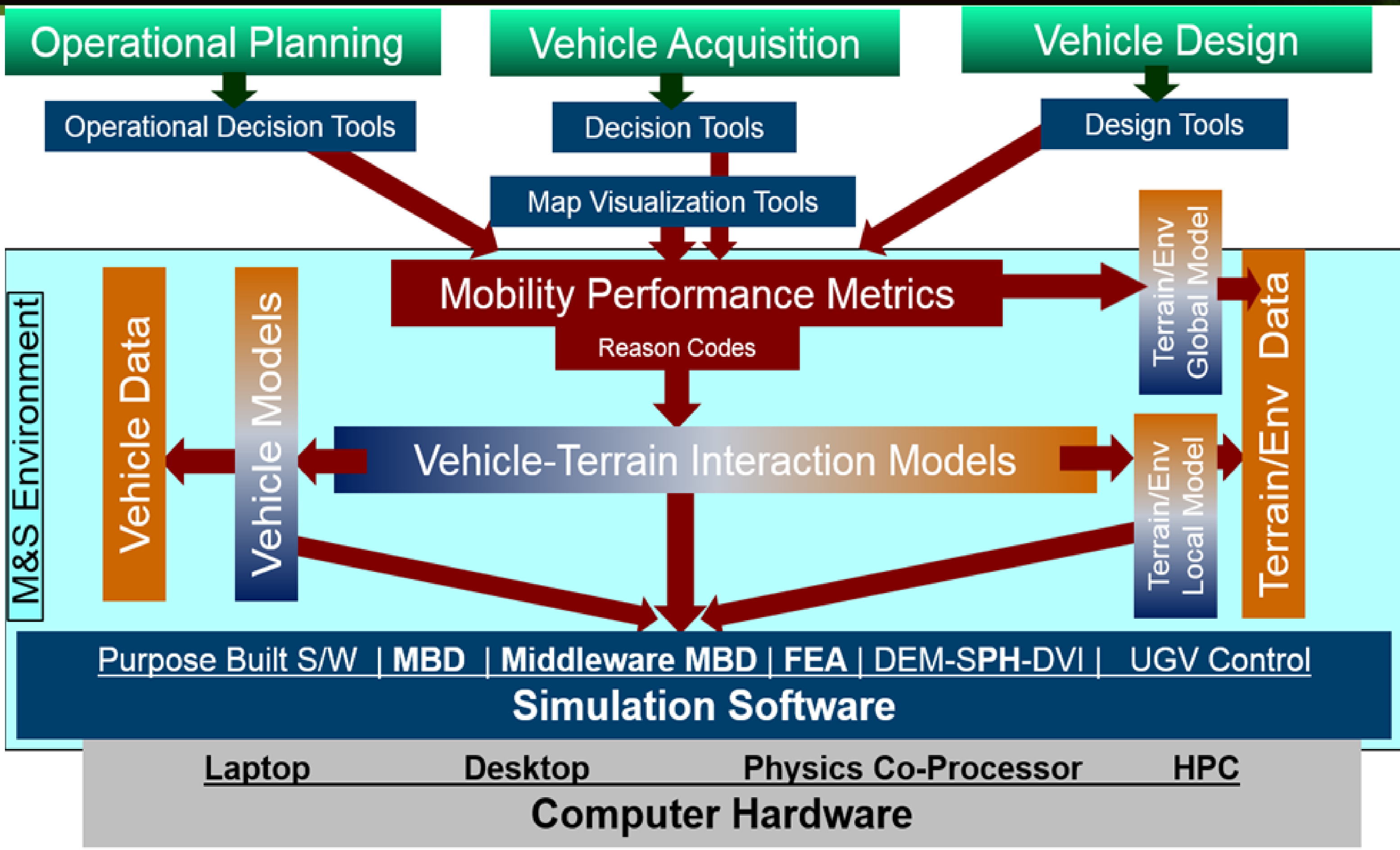
By establishing formal NATO mobility modeling standards, NG-NRMM will leverage the latest commercial modeling tools and data sets

Methodology: Phased Development

Model Component	Model Accuracy and Resolution			
	Empirical Current	Empirical Enhanced	Open Architecture Model: Threshold	Open Architecture Model: Objective
	NRMM Standard Release	NRMM With Substitutions	Threshold NORMMS	NORMMS
Mobility Mapping	NRMM Operational Module	NRMM Operational Module	Modified NRMM Operational Module Integrated to GIS s/w	Modular, Expandable, Documented, Verified, Mobility Mapper with Long Term NATO CM support
Off-Road Mobility	NRMM	NRMM+	Bekker/Wong, Height Field	FEM / DiscreteEM
Vehicle Dynamics	VEHDYN (2D)	3D MBD	Ftire, Multilink track	Integrated Deformable dynamic terrain
Intelligent Vehicle	Constant speed	Variable speed	Closed loop 3D path following with sensors	AI with analytical sensor-terrain interaction in feature-rich environments
Compute Platform	Desktop	Desktop	Multi-Threaded Desktop	HPC

The two phased development process proposes to establish threshold NG-NRMM standards within 3 years and set long term goals for mobility research and development

Methodology: Adaptable Data and Requirements Flow Standards



NG-NRMM standards will recognize end-user requirements by remaining flexible with respect to mobility metric definitions, data levels of resolution and M&S availability

Open Architected NG-NRMM Operational module

- Decompose current NRMM Operational module data sets and algorithms
- Develop speed made good and GO/NOGO standard definitions with expected simulation based input data
- Translate to written standards and benchmarks
- Identify durable implementation environments such as a high level flexible scripting language like Python

NG-NRMM standards will leverage the legacy data and algorithms, but use open architecture environments to promote inclusive and evolutionary future capability growth

Leveraging Stochastic Simulations

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Raw DEM
(10×10 [km^2])
NO SOIL INFO

Resol. = 30 [m]

Resol. = 30 [m]

HPC

Kriging (interpolation to a finer resolution)

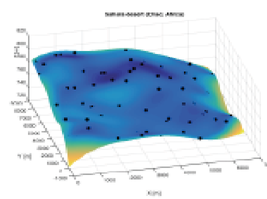
Resol. = 10 [m]

DEM subsampling
(set of representative points)

Resol. = Depends on the setup (e.g. 30-m)

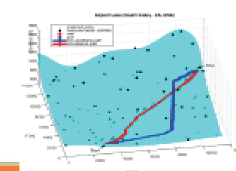
Kriging (interpolation to a finer resolution)

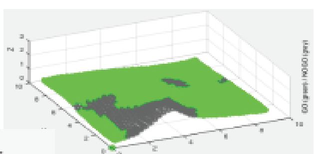
PC (our approach)

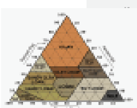


Resol. = 10 [m]

New DEM (10×10 [km^2], 10-m resol.)







Mobility maps

Terrain profile and soil properties

Deterministic GO/ NOGO map
$Z = \bar{Z}$

Stochastic GO/ NOGO map
$Z = N(\bar{Z}, \sigma)$

Route planning

Deterministic DEM

Path planning

Route 1 (min-distance)

Route 2 (min-uncertainty)

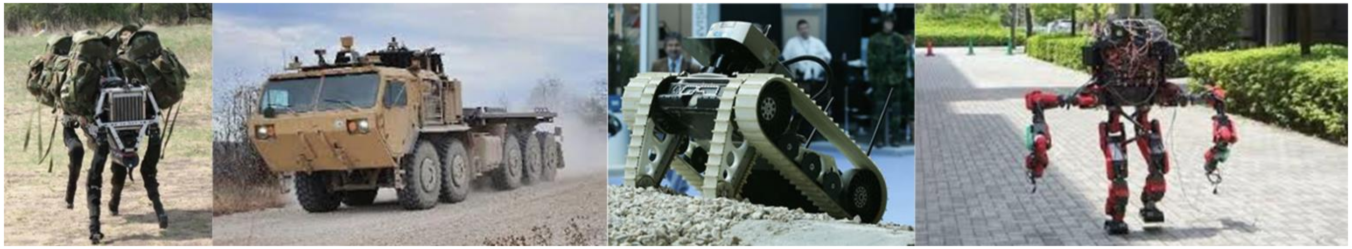
Route 3 (min-slope)

Statistical analysis

NG-NRMM standards will leverage the state of the art tools for stochastic methods in geospatial modeling and simulation

Intelligent Vehicles

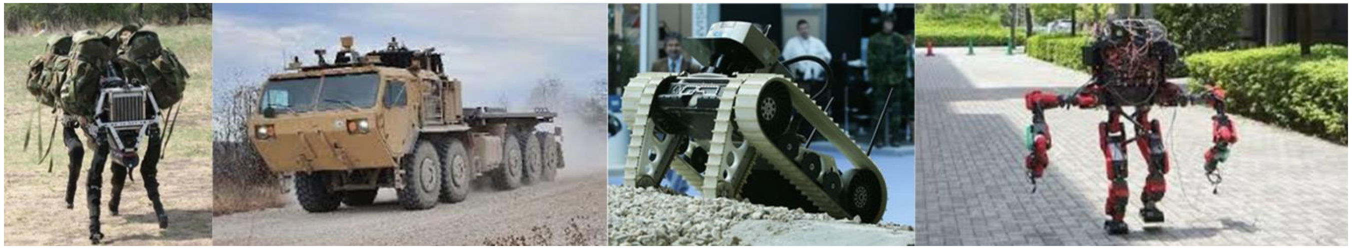
- At an M&S architectural level, vehicle intelligence (VI) can be viewed as a broader more intensive form of embedded automatic control systems such as anti-lock brakes, traction control, controlled suspension systems, etc.
- VI is an essential element of NG-NRMM from two perspectives:
  - tailored VI related mobility metrics
  - embedded validated NG-NRMM models into VI algorithms



NG-NRMM standards will encompass the broader definitions of terrain and vehicle morphologies that are characteristic of intelligent vehicle applications

Intelligent Vehicles: Requirements

- All ground vehicle morphologies
- urban and building interior environments
- multiple levels of model resolution
- stochastic modeling and learning VI algorithms
- hierarchical and skill-based sliding scale of autonomy
- VI related mobility metrics, for example:
  - Look ahead speed limit:
  - Generalized customizable ride quality
  - Speed through an offset corridor
  - Soft soil limit sensing performance



Tool Choices: Trade Study of Simulation SW Capabilities

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MOE	MOP	MOE Weight	MOP Composite Weight
Accuracy / Robustness	Physics based	37.5%	16.7%
	Validation through measurement		12.5%
	Supports time and frequency domain analysis		8.3%
Flexibility	Template based	37.5%	8.3%
	Wheeled or tracked vehicles		20.8%
	Automotive Subsystems		8.3%
Cost, Maintenance, and Run Time	License	12.5%	5.6%
	Run Time		2.8%
	Training		4.2%
NATO Specific Applications	Supports unique terrain or mission definition	12.5%	6.9%
	Worldwide tool availability to approved sources		2.8%
	Worldwide tool support		2.8%
		100.0%	100%

Tool Choices: Survey Results

- The detailed scores revealed that
  - Accuracy for vehicle system performance is the biggest shortfall of the current NRMM when compared to other M&S sources.
  - Validated physics-based methods are a recognized improvement over the current empirical methods for simulating vehicle and suspension designs.
  - Industry wide shortfall with <u>tire dynamics</u> and <u>soft soil behavior</u>.

NG-NRMM Input and Output Data Standards

- Develop Vehicle, Terrain, Driver, and Weather Scenario Modeling Data Standards
- Data Interoperability Standards with COTS GIS mapping tools (e.g. Open Geospatial Consortium (OGC))
  - High resolution satellite imagery / remotely-sensed GIS data transformed into accurate NRMM terrain representations.
- Ensure consistency of data over the sliding scale of model resolutions

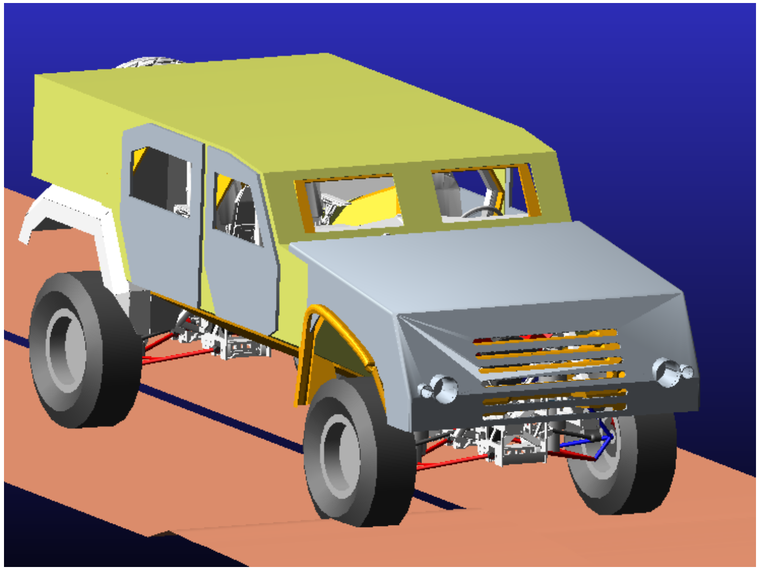
Verification and Validation: M&S Benchmark Events

1. Steady State Cornering and Steering Performance (pavement and soft soil)
2. Double Lane Change with Autonomy (pavement and gravel)
3. Side Slope Mobility (pavement and soft soil)
4. Grade climbing (pavement and soft soil)
5. Ride and Shock Quality (standard NRMM definitions initially)
6. Obstacle Performance (standard NRMM definitions initially)
7. Off-road Trafficability (new soil strength metrics)
8. Fuel Economy (3D course, pavement and soft soil)

Verification and Validation
Benchmark Generic Vehicle Models

- Tracked vehicle based on data set from [Wong, et al., 1984] with arbitrary assumptions on missing data for a complete 3D vehicle dynamic model
- Wheeled vehicle model (TBD) will be a 4x4 with a similar linkage to a real vehicle.
- Consistent with principles of open source development, participants are encouraged to provide suggestions for improvement and expansion of the benchmarks

[Wong, et al, 1984]



NG-NRMM M&S Capability Maturity Model

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NG-NRMM M&S Capability Maturity Levels	
Level 1.	DEMONSTRATION: Vendor demonstration
Level 2.	VERIFICATION: Independent user demonstration and correlation to vendor results
Level 3A.	CROSS CODE VERIFICATION: Cross verification with another accepted mobility simulation code, or accepted physics principles
Level 3B.	PARAMETER SENSITIVITY VERIFICATION: Verification that performance change with a change in system parameter is consistent with theory and physics principles.
Level 4.	CALIBRATION: Calibration to a real vehicle test data set
Level 5.	VALIDATION: Blind correlation to a real vehicle test data set
Level 6.	PARAMETER VARIATION VALIDATION: Blind correlation to a real vehicle test data set with a change in system parameter(s).

The NG-NRMM V&V team has established a progressive scale of achievement that will promote collaboration and investment by industry stakeholders.

Path Forward

NATO Research Task Group (RTG-248) will carry forward six research goals:

1. GIS-Terrain and Mobility Mapping: Identify a GIS-based mapping tool that implements and integrates existing valid mobility metrics (%NOGO and Speed Made Good) in an open architected environment.
2. Simple Terramechanics: Identify most promising existing terramechanics methods supporting NG-NRMM requirements that provides possible means of correlating the requisite terrain characteristics to remotely sensed GIS data.
3. Complex Terramechanics: Establish a vision for the long term terramechanics approaches that overcome the limitations of existing models.

Path Forward (continued)

4. Intelligent Vehicle Mobility: Identify unique mobility metrics and M&S methods necessary for predictions supporting mobility assessments of intelligent vehicles over a sliding scales of data and control system resolutions.
5. Uncertainty Treatment: Identify the practical steps required to embed stochastic characteristics of vehicle and terrain data to extend and refine the current deterministic mobility metrics.
6. Verification & Validation (V&V): Implement near-term vehicle-terrain interaction benchmarks for verification of candidate NG-NRMM M&S software solutions and lay the groundwork for long term validation data through cooperative development with test organizations standards committees.

Thank You